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Soil Fertility, Fertilization and Growth of Canadian Forests

N.W. Foster and I.K. Morrison

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SOIL FERTILITY, FERTILIZATION AND GROWTH OF CANADIAN FORESTS[1]

N.W. FOSTER AND I.K. MORRISON

GREAT LAKES FOREST RESEARCH CENTRE

CANADIAN FORESTRY SERVICE

DEPARTMENT OF THE ENVIRONMENT

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ABSTRACT

Fertilizer test plots have provided the best evidence for assessing soil nutrient-supplying ability in relation to tree demand. Results from experiments in adult forest across Canada and the adjacent United States support the hypothesis that lack of N generally limits growth of some coniferous species, especially on drier sites. Responses to P and K are reported only occasionally; e.g., red pine *(Pinus resinosa* Ait.), on outwash sands abandoned from agriculture, produced 25 to 80 m^3 ha^{-1} of extra wood over 5 to 10 years after fertilization with K. With many species additional growth is realized when P and/or K are added with N, but generally response is not significantly greater than with N alone.

The addition of urea (224 kg N ha^{-1}) to natural stands produced, on average, an additional 15.6 m^3 ha^{-1} of wood over 4 years with Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco) and 8.5 m^3 ha^{-1} over 5 years with jack pine *(Pinus banksiana* Lamb.). In Douglas-fir and jack pine forest, inverse relationships between site index and response to N have been found, the greatest growth increase being on poorer sites. Average 5-year responses were less with balsam fir *(Abies balsamea* [L.] Mill.), red spruce *(Picea rubens* Sarg.), white spruce *(P. glauca* [Moench] Voss), and black spruce *(P. mariana* [Mill.] B.S.P.) (7.1, 4.6, 4.5, and 2.2 m^3 ha^{-1}, respectively).

The use of foliar diagnosis and soil chemical analyses to determine which forests respond to fertilization is discussed.

RÉSUMÉ

La fertilisation en parcelles expérimentales a fourni la meilleure base pour évaluer l'aptitude du sol à répondre aux besoins des arbres en éléments nutritifs. Les résultats d'expériences dans des forêts adultes du Canada et de régions contiguës des É.-U. appuient l'hypothèse que la carence en N limite généralement la croissance de certains conifères, spécialement dans les stations sèches. Ce n'est que parfois que les réactions à P et à K sont signalées; par exemple, du pin rouge *(Pinus resinosa* Ait.), sur les sables incultes d'épandage fluvio-glaciaire, qui produit 25 à 80 m^3/ha de plus de bois, en 5 à 10 ans, après la fertilisation avec K. Beaucoup d'essences croissent davantage quand P, K ou les deux sont ajoutés à N, mais généralement la réaction n'est pas significativement plus grande qu'avec N seul.

L'apport d'urée (224 kg/ha de N) à des peuplements naturels donne en moyenne 15,6 m^3/ha de plus de bois, en 4 ans, chez le Douglas taxifolié. *(Pseudotsuga menziesii* [Mirb.] Franco) et 8,5 m^3/ha, en 5 ans, chez le pin gris *(Pinus banksiana* Lamb.). Dans les forêts de Douglas taxifolié et de pin gris, on a observé des relations inversement proportionnelles entre l'indice de station et la réaction à N, la plus grande augmentation de croissance survenant dans les stations pauvres. En 5 ans, les augmentations moyennes ont été inférieures chez le sapin baumier *(Abies balsamea* [L.] Mill.), l'épinette rouge *(Picea rubens* Sarg.), l'épinette blanche *(P. glauca* [Moench] Voss) et l'épinette noire *(P. mariana* [Mill.] B.S.P.) [7,1, 4,6, 4,5 et 2,2 m^3/ha, respectivement].

L'étude traite du diagnostic foliaire et des analyses chimiques du sol comme moyens de déterminer quelles forêts réagissent à la fertilisation.

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INTRODUCTION

Soil fertility is the status of a soil in relation to the quantity of each element necessary for plant growth, and its availability to plants (Anon. 1976). Soil fertility, as well as other soil properties (moisture, temperature, depth), climate, physiography, species characteristics, stage of growth, and nature of management determine the productivity of forest crops.

Forest soils are generally of lower fertility than those associated with agriculture. The dominant soil order is Podzolic, although Brunisolic, Luvisolic, Gleysolic and Organic soils support considerable areas of forest growth (Rennie 1972). The range of soil conditions is large, but in Canada, medium- to coarse-textured acidic soils and soils with appreciable stone and boulder content predominate. The more productive soils are fine-textured silts and clays (Lowry 1975). The poorest tree growth occurs on gravelly sands or on deep peat (Page 1971, Lowry 1975).

The volume of wood to be derived from a forest stand is governed by three main factors: density of stand, site quality (index) and stand age. Stand density is conventionally measured as basal area (cross-sectional area of living tree stems at 1.37 m above ground). Site quality is determined by site index, the average height of dominant trees at a specified common age. The influence of soil and site factors on growth may be less than that of age and stocking (Duffy 1965); therefore, it may be desirable to keep the latter constant when studying relationships between growth and soil-site properties.

The unmanaged natural semimature forests of the Coastal, Boreal and Acadian forest regions, from which the bulk of our information on soil fertility and forest fertilization has been derived, exhibit extremes of forest growth rates in $m^3\ ha^{-1}\ yr^{-1}$ of from 1 to 35 in the Coastal to 1 to 5 in the Boreal. In the Acadian region growth equals or surpasses that of the better Boreal sites. For a given basal area and age, the volume growth increases with increase in site quality. As an example, Evert and Lowry (1970) reported for black spruce that better-quality sites produced two to four times more growth than poorer sites.

That soil nutrient levels may limit forest productivity in Canada was first suggested by Lafond (1958) and Swan (1962) after examination of leaf materials from red pine *(Pinus resinosa* Ait.) and white spruce *(Picea glauca* [Moench] Voss) plantations near Grand'-Mère, Quebec. The outwash sands supporting the plantations had been exhausted of nutrients by agricultural practices and abandoned, and could produce only mineral-deficient forest with poor growth and appearance. Increased growth was achieved when potassium (K) and magnesium (Mg) were added to the soil (Lafond 1958, Gagnon 1965). Red pine on abandoned farmland in Ontario has also been shown to respond to nitrogen (N) together with phosphorus (P) and K fertilizers (Leech 1965, 1967).

General insufficiencies of elements in soil, however, are less readily apparent than are extreme deficiencies. Fertilizer test plots have provided the best evidence for assessing soil nutrient-supplying ability in relation to tree damand. Positive growth responses in fertilizer

trials in Scandinavia (e.g., Carbonnier et al. 1969) and the northwestern United States (Gessel et al. 1969) served as a stimulus to Canadian studies on fertilization of natural forest. These experiments and others (e.g., Möller 1972, Braastad et al. 1974) were instrumental in establishing forest fertilization as an operational practice in these locations.

As early as the mid-1950s, N was recognized as an important element limiting growth of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in British Columbia (Crossin et al. 1966). Reports by Weetman (1968), Hoyt (1973) and van Nostrand and Bhure (1973) indicated that responses to fertilizers, particularly N, could also be realized in eastern natural coniferous forest. Reviews by Rennie (1972) and Armson et al. (1975) describe these trials and their initial results. During the period since these various reviews were published, interim (5-year) results of a number of fertilizer trials begun in the late 1960s and early 1970s by industry, universities, and both provincial and federal governments have been published. Among these studies, for example, is the Interprovincial Forest Fertilization Program, comprising 79 standardized experiments established by the provincial forest services of Alberta, Manitoba, Ontario, Quebec and New Brunswick and by the Canadian Forestry Service in Saskatchewan and Nova Scotia. Some preliminary conclusions have been drawn from analysis of the data from these experiments. The objective of the present report is to determine what these fertilizer trials can tell us about soil fertility and its influence on productivity of forest soils.

FERTILIZER TRIALS

Age

Fertilizers have been used in forestry, in nurseries, at time of plantation establishment, and at the juvenile, immature and semimature stages of forest development.

Additions of fertilizer to forest nurseries are required to realize optimum production of nursery stock (van den Driessche 1963, Armson and Sadreika 1974).

On the other hand, the nutrition of forest up to 10 years of age has received very little attention. Von Althen (1976) reported the results of three experiments on which NPK fertilizers were broadcast on abandoned farmland at time of planting. The species planted were basswood (*Tilia americana* L.) and red oak (*Quercus rubra* L.) on sandy loam soils and silver maple (*Acer saccharinum* L.) and black walnut (*Juglans nigra* L.) on clay loam soils. Even with weed competition controlled by herbicides, von Althen found that broadcast fertilization produced no increase in foliar N, P and K concentrations and no improvement in height growth over unfertilized trees during the first five years of growth. In a fourth experiment, placement of P at the bottom of planting holes increased P concentrations in black walnut and white ash (*Fraxinus americana* L.) leaves but failed to improve height growth. Fertilization of a 5-year-old (Calvert and Armson 1975) and a 10-year-old (Winston 1977) jack pine (*Pinus banksiana* Lamb.) plantation likewise failed to stimulate height growth. Low per-hectare demand initially from seedling- and sapling-age forest coupled with accelerated

nutrient release from the decomposition of surface organic material (Page 1974) and large quantities of slash, particularly nutrient-rich needles and bark on cutovers, may explain the lack of response to fertilizers by these young forests.

The addition of N to immature 20- to 30-year-old natural jack pine forest[2], a 20-year-old red spruce *(Picea rubens* Sarg.)-white spruce-balsam fir *(Abies balsamea* [L.] Mill.) plantation (Timmer and Fisher 1978) and a 30-year-old western hemlock *(Tsuga heterophylla* [Raf.] Sarg.) forest[3] had no effect on growth, and this suggests that immature stands may not respond to fertilization either. Positive growth responses by 15-year-old Douglas-fir forest[4] and 25-year-old western hemlock (Webster et al. 1976) were not consistent with this generalization, however. In the latter study, additional response to fertilization was realized when the forest was thinned before fertilizers were applied.

Most fertilizer trials, however, have been conducted in semimature natural forest, usually uniform, relatively fully stocked, even-aged stands of either single coniferous species or simple mixtures of conifers. The rationale for fertilizing semimature forest was to increase yield with a single application of fertilizer 10 years or so before harvest, so that carrying charges on investment could be minimized. Additional gain from fertilization of semimature forest might be realized where greater diameter growth increases the number of trees that are merchantable for harvesting. The most commonly used fertilizers are urea as a source of N, triple superphosphate for P and potassium chloride for K.

Nitrogen Response

The results from a large number of experiments in adult forest across Canada and the adjacent United States support the hypothesis that lack of N limits the growth of at least some coniferous species. The responses of Douglas-fir and jack pine were generally positive and often statistically significantly greater than the growth of unfertilized forest (Table 1). Jack pine responded well to fertilization with the largest percentage increase in growth over controls, whereas Douglas-fir produced the largest volume of wood attributable to fertilization. These species are commonly found on less-fertile, deep, loamy sands and gravelly sandy loams.

The responses of balsam fir and white spruce were generally positive also, but in many trials the results were not statistically significant. These species are commonly associated with sandy loam to clay loam tills of higher inherent fertility, although some are compacted and shallow and therefore of restricted rooting. Black spruce showed the poorest response over all: in a number of experiments, growth of fertilized trees was less than that of unfertilized trees. Lowry (1975) found black spruce with high site indices on fine-textured silts and

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[2]Kelertas, R.D. 1977. Growth response of immature jack pine *(Pinus banksiana* Lamb.) to nitrogen (urea) fertilization--fifth year results. Univ. Toronto, unpubl. rep.).

[3]Rottink cited by Miller 1976.

[4]Gessel cited by Miller 1976.

clays and spruce with medium and low indices on medium- and coarse-textured loams and sands. The results from some of the balsam fir and spruce stands were influenced by mortality and crown damage associated with a spruce budworm epidemic in eastern Canada. Nonuniform stand and soil conditions may also have contributed to nonsignificant responses in those cases in which positive increases in volume were recorded.

Table 1. Five-year total volume response of coniferous forest to fertilization with 224 kg N ha^{-1} as urea[a].

	Total volume increase over control			
	Max	Min	Avg	Avg
Species	(m^3 ha^{-1})			%
Douglas-fir[b]	25.6[c]	7.6[d]	15.6	18
jack pine	19.1	-2.7	8.5	35
balsam fir	15.7	-3.8	7.1	24
red spruce	10.9	-1.9	4.6	18
white spruce	14.5	-1.9	4.5	16
black spruce	8.4	-7.8	2.2	10

[a]Data from Gessel 1977; Morrison et al. 1976a, b, c; Weetman et al. 1976, 1978, 1979

[b]4 years

[c]Mean for site IV Douglas-fir

[d]Mean for site I Douglas-fir

Nitrogen Source

Urea was the source of N in almost all Canadian experiments. In Sweden, volume-growth increases by Scots pine (*Pinus sylvestris* L.) have averaged 30% higher with ammonium nitrate than with urea (Braastad et al. 1974). Poorer growth responses to urea have been related to volatilization of N, delayed hydrolysis of urea to ammonia, and microbial immobilization of fertilizer N in humus.

In Canada, comparison of foliar N concentrations produced by the two fertilizers does not show conclusively that one fertilizer is superior to the other. Weetman et al. (1972) found higher first-year foliar N concentrations and needle weights with urea application to boreal black spruce but higher foliar N with ammonium nitrate during the first three years after fertilization of black spruce in the Acadian forest region (Weetman et al. 1974). Ammonium nitrate produced higher first-year foliar N concentrations than did urea in a boreal jack pine forest (Weetman and Algar 1974). In spruce, despite higher foliar concentration associated with ammonium nitrate (Weetman et al. 1974), urea produced greater basal area increments, although the response was not significantly different from that produced by ammonium nitrate. Likewise, no clear superiority of one N-source over the other, in terms of increased growth of semimature jack pine, was noted by Morrison et al. (1976a, 1977a) or Weetman and Algar (1974). In the first study, total and merchantable volume increments produced by the two fertilizers were identical; in the second, urea produced greater gains than ammonium nitrate after 10 years; in the third, ammonium nitrate produced greater gains in basal area over three years than did urea. Comparisons of ammonium nitrate with urea in western hemlock forest have likewise produced inconclusive results (Webster et al. 1976).

These North American studies, though few in number and somewhat inconclusive in results, do not support the superiority of ammonium nitrate that has been demonstrated in Sweden. Further studies are required to resolve this important question of source of N.

Length of Response

Growth increases after fertilization have been correlated with increased needle weight and foliar nutrient concentrations (Krause 1973, Weetman and Algar 1974). If such correlations hold, assessment of the duration of response to fertilizer addition could be made by following needle parameters. With young trees, however, Calvert and Armson (1975) reported that fertilization increased needle weight and nutrient concentration without increasing height growth of jack pine.

Declines in foliar-N concentration to control levels within 2 to 3 years of fertilization with 100 to 300 kg ha^{-1} of urea-N have been reported for red spruce (Safford et al. 1977) and white spruce (Salonius 1978). Within 2 to 3 years after fertilization with urea at a similar rate, foliar concentrations remained above those in untreated forest in jack pine (Morrison, unpublished data), balsam fir (Truong-dinh-Phu and Gagnon 1975) and Douglas-fir (Lee 1971). Weetman (1971) recorded increased foliar N concentrations for 4 years after an addition of 112 kg urea-N ha^{-1} to black spruce, whereas after a 448 kg ha^{-1} addition, foliar levels were still higher than those in control forest after 10 years (Weetman 1975). The results of foliar analysis therefore indicate that most of the response to urea is likely to occur in the first 2 to 4 years after fertilization.

Duration of growth response is dependent on the quantity of N applied. Peak growth responses to 100 - 150 kg N ha^{-1} by Douglas-fir (Miller and Pienaar 1973, Lee 1974) and black spruce (Weetman 1971) occurred in the second or third year--this was in general agreement with responses predicted by foliar tests--and declined rapidly thereafter. With higher N applications, peak response did not occur until the fifth (Miller and Pienaar 1973) or seventh to eighth growing seasons (Weetman 1975) and a sustained response into the seventh to tenth growing seasons was indicated in these studies. A somewhat similar effect has been noted in jack pine when P and K were added with N (Morrison, unpublished data). Although these initial results do give some indication of duration of response to fertilization, considerably more information on the length and magnitude of response will be available when the 10-year remeasurements of the trials initiated in the late 1960s and early 1970s are reported.

The optimum amount of urea-N for maximum growth of a 45-year-old jack pine stand was 200 kg ha^{-1} (Fig. 1). This rate produced the optimum response in two other eastern conifers of semi-mature age: black spruce (Weetman 1971) and balsam fir (Gagnon 1973).

Phosphorus and Potassium Response

Growth response to single applications of P and K on mineral soil have been reported for black spruce (Krause 1973, van Nostrand and Bhure 1973) and mixed spruce-fir (Krause 1973). Balsam fir in New Brunswick responded to K but not to N and P (ibid.). Furthermore, there was a significant correlation coefficient for the relationship between foliar K in current needles and

basal area growth. Red pine and white spruce plantations on outwash sands abandoned from agriculture have responded well to fertilizers, particularly K, producing 25 to 80 m^3 ha^{-1} of extra wood over 5 to 10 years (Heiberg et al. 1959, Leech 1965, 1967, Gagnon et al. 1976). In the other experiments the responses to P and K were lower than the response to N, and this supports the hypothesis that N is the element of prime importance to coniferous forest growing on mineral soils.

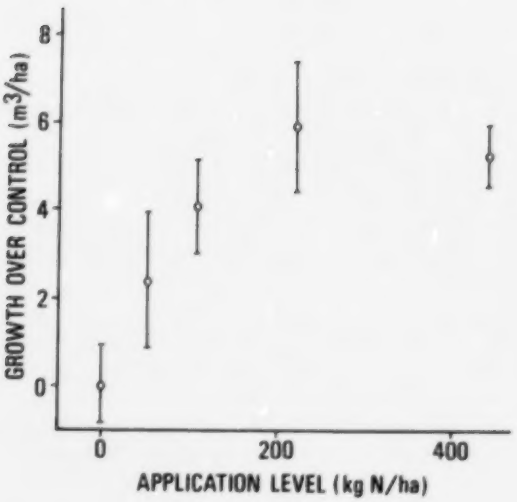

Figure 1. Five-year volume growth-over-control of 45-year-old jack pine forest in relation to urea application level (means ± standard errors) from Morrison et al. 1976c).

When P and K were added with N, additional growth was often realized (Table 2), but generally responses were not significantly greater than when N alone was used. A combination of N and K fertilizers produced the best average response in jack pine and balsam fir. Black spruce was most responsive to N plus P and white spruce to N alone and N plus P.

Lack of significant response is related partly to insufficient treatment replication in many experiments. Furthermore, these results are derived mainly from experiments in which one or rarely more than one level of K or P was added with N. If an optimum response surface were developed the yields might be further improved. An example of a response surface for N-P-K application to jack pine in Ontario is presented in Figure 2.

Species-Site Interaction

Species-site interaction in relation to tree nutrient demand and soil nutrient supply makes it difficult to draw firm conclusions with respect to the role of soil fertility and response to fertilization. An example of how species differ in their nutrient requirements is presented in Table 3, which shows the nutrient contents of four species growing on the same soil, a sandy loam developed from calcareous till. There was a considerable difference in nutrient accumulation between species despite the fact that the aspen *(Populus tremuloides* Michx.), white spruce and jack pine forests had similar dry-matter contents. Aspen and spruce accumulated the greatest quantity of nutrients, and exhibited a particularly high demand for calcium (Ca). Jack pine accumulated less of every nutrient than did the other

Table 2. A summary of total volume response to combinations of N, P and K fertilizer[a].

Species	No. of expts.	Distribution among treatments of maximum response				Avg response best treatment (m^3 ha^{-1})	Avg response to N (m^3 ha^{-1})
		N	NP	NK	NPK		
		%					
jack pine	29	3	28	52	17	13.2	8.1
balsam fir	15	27	20	47	6	9.3	6.9
black spruce	25	16	48	12	24	5.4	2.4
white spruce	5	40	40	20	0	4.5	4.5

[a]Data from Foster (unpublished); Hoyt 1973; Krause 1973; Morrison et al. 1976a, b, 1977b; Morrison and Foster 1979; van Nostrand and Bhure 1973; Weetman et al. 1976, 1978, 1979.

species. Black spruce, white spruce and balsam fir, growing in a northern Ontario mixedwood forest on an upland till, did not respond to N and P, whereas white birch in the same stand responded well (Morrison and Foster 1979).

A soil may therefore provide adequate nutrition for some species, but be deficient in nutrients for others. Where black spruce and jack pine occur in mixture, pine responds to fertilization better than spruce (Weetman et al. 1976, 1979).

Data from 27 separate fertilizer trials in jack pine forest in which urea-N was applied at 112 or 224 kg ha^{-1} were used to show a general inverse relationship between site index and response to N (Table 4). The greatest growth increases were associated with the stands of lowest site index. The validity of the relationship is questionable, because there were only a few observations in site III forest. Gessel (1977) likewise found an inverse relationship between site index and Douglas-fir response to application of 224 and 448 kg urea-N ha^{-1} in a study involving 200 trials in Oregon and Washington.

Using height/age as an index of site is attractive because tree height growth is relatively independent of stand density. Site index, however, interprets all the patterns of growth that the tree experiences during its lifetime, and thus may not reflect how the tree is growing at present. An alternative might be to use diameter growth to assess current growth rates, but the inverse relationship between diameter growth and stand density is a drawback. Chrosciewicz (1963) reported that jack pine site indices based on breast height diameters varied in a way similar to those based on heights, when

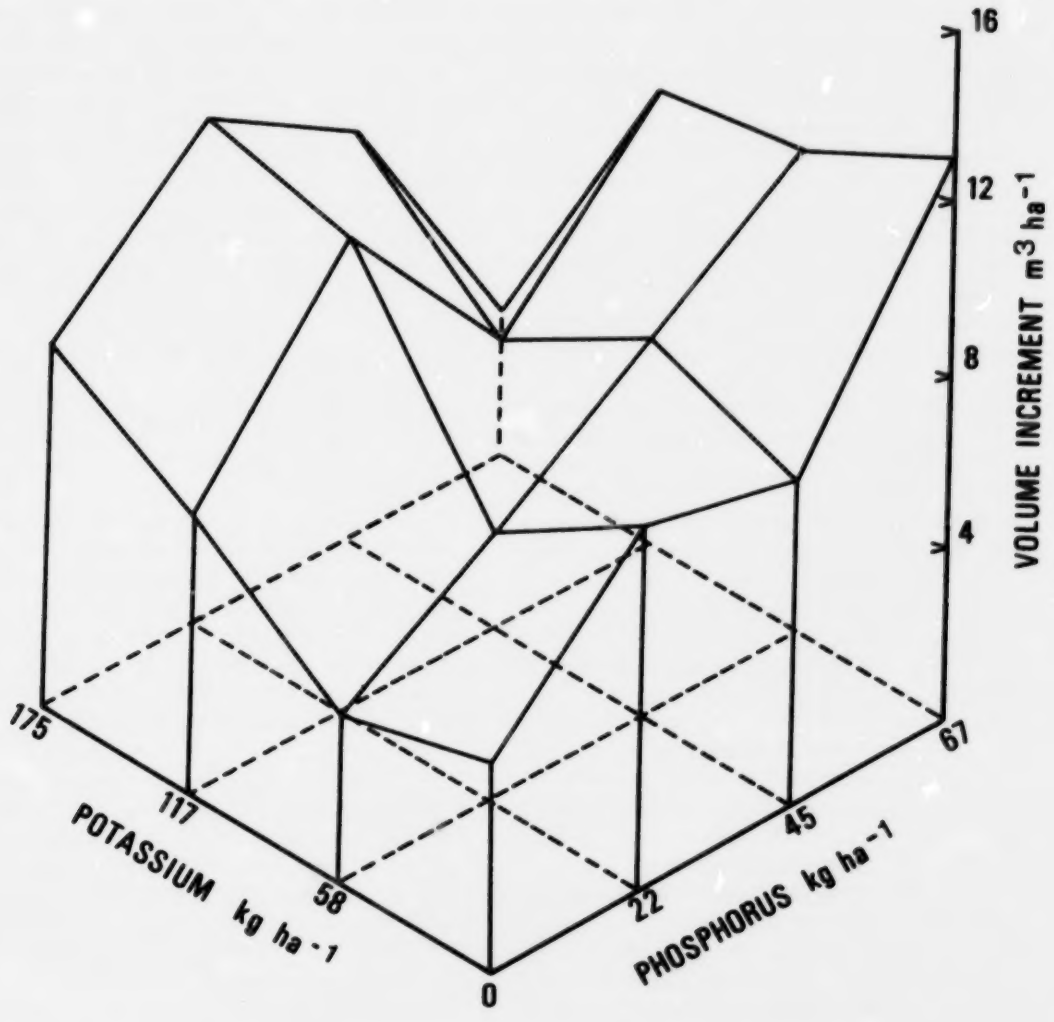

Figure 2. Effect of phosphorus and potassium with nitrogen on 4-year volume growth-over-control of 55-year-old jack pine (data from Morrison et al. 1976a).

Table 3. Dry matter and nutrient content (kg ha^{-1}) of 40-year-old forest on a sandy loam soil developed from calcareous till.[a]

Species	Dry matter	N	P	K	Ca	Mg
aspen[b]	166 800	457	67	367	1074	76
white spruce[c]	150 800	449	64	254	809	46
red pine[c]	199 400	421	50	205	335	72
jack pine[c]	147 300	296	30	119	241	46

[a]Data are from Alban et al. 1978.

[b]Natural forest.

[c]Plantation (1 x 1.5 m spacing).

Table 4. Five-year volume growth-over-control (m^3 ha^{-1}) of jack pine in response to fertilization with urea. (mean with range in parentheses)[a]

Treatment (kg N ha^{-1})	Site class[b] III (11 m - 13.6 m)	II (13.7 m - 16.7 m)	I (16.8 m - 19.8 m)
112	8.3 (5.8 - 12.1)	6.2 (1.6 - 15.9)	4.8 (-.8 - 10.4)
224	13.1 (9.7 - 19.1)	8.7 (0.9 - 17.8)	6.7 (-2.7 - 17.8)

[a]Data from Morrison et al. 1976a, c, Weetman et al. 1976, 1978, 1979.

[b]Plonski 1974.

sampling was restricted to fully stocked stands. Since most fertilizer trials have been located in uniform fully stocked stands, the use of current volume growth (measurable as current or periodic annual increment), which integrates both diameter and height, may be justifiaole. A relationship between stand vigor as measured by current annual increment and black spruce foliage-N concentration has been demonstrated by Lowry and Avard (1968). As most of the black spruce experiments published were located in site class I forest (Plonski 1974) a comparison of site index and response to fertilization would not be possible. Therefore, we compared the volume response of black spruce and jack pine as a function of periodic annual increment at age 50 (Table 5). For both pine and spruce the slower-growing forest (PAI_{50} 2-3.9) showed the best response to both levels of fertilization. Stands with a PAI_{50} of 6.0 or better appear to be a poor risk for fertilization. There was a wide range in volume increment produced as a result of fertilization, however, and examples of good responses and poor responses were noted in all site classes (Table 4) and PAI_{50} classes (Table 5). Therefore, additional studies are required to validate these suspected site/growth rate response relationships.

Despite results from numerous experiments we are unable to determine whether or not a forest will respond to fertilization. The number of positive responses and the magnitude of response to fertilization, particularly jack pine and Douglas-fir response to N, are encouraging and justify continued effort toward defining the response surface so that the maximum potential response to fertilization is documented, and toward identifying those sites that respond best to fertilization. In the following section the contribution that soil and foliar diagnosis can make toward identifying sites with soil fertility problems and a potential to respond to fertilization will be examined.

IDENTIFICATION OF MINERAL DEFICIENCIES

Foliar Analysis

Deficiencies in which observable morphological abnormalities appear are generally restricted to nurseries and intensively managed forest. Foliar chemical analysis has been a particularly valuable aid in diagnosing nutrient deficiencies in nurseries and juvenile plantations. With reference to the southeastern United States, Ballard and Pritchett (1975) state that "foliar analysis and soil testing are the two most commonly used procedures for predicting fertilizer requirements for southern pine plantations with foliar analysis the more effective." In plantations, stocking is optimized, production is increased, and a high demand for nutrients is therefore placed on the soil. Truong-dinh-Phu and Gagnon (1975) have used multiple correlation analysis to demonstrate a positive and significant relationship between foliar K and growth (basal area and total volume) of white spruce plantations on marine sands abandoned from agriculture (r^2 = .6). Truong-dinh-Phu (1975) also found a significant and positive linear correlation between site index and concentrations of K and Mg in red pine foliage (for K, r^2 = .5).

Table 5. Annual volume growth-over-control (m^3 ha^{-1} yr^{-1}), over 5 years, of jack pine and black spruce in response to fertilization with urea as a function of PAI (m^3 ha^{-1})[a].

Treatment (kg N ha^{-1})	Species	Periodic Annual Increment		
		2 - 3.9	4 - 5.9	6.0+
112	jack pine	1.5	1.1	0.8
	black spruce	0.7	0.5	0.2
224	jack pine	1.8	1.7	0.8
	black spruce	0.6	0.5	0.2

[a]Data from Foster (unpublished); Morrison et al. 1976a, b, c; Weetman 1968; Weetman et al. 1976, 1978, 1979.

In natural, unmanaged, mature forest, severe deficiencies are not usually observed. Because of seasonal patterns of nutrient concentration in foliage and within-crown variation related to age and position of needles, particular care must be exercised in the selection of foliar materials (Lowry and Avard 1969, Morrison 1972, Ellis 1975). When rigid sampling procedures are followed, differences between good and poor growth have been correlated with foliar nutrient concentrations. For example, significant positive linear correlations between growth as indicated by site index and the N concentration of black spruce foliage have been reported by Gagnon (1964) and Lowry and Avard (1968). Webber (1974) found that N in current foliage of Douglas-fir was significantly related to site index. These results also support the hypothesis that there is a general N deficiency in northern coniferous forests.

Swan (1970, 1971, 1972, etc.), by solution culture, estimated critical foliar level of macroelements for various coniferous species. To aid in diagnosis of nutrient deficiency in mature forest, he adjusted his pot-culture derived indices to concentrations of nutrients normally found in adult forest. Since a number of fertilizer trials have reported both growth and pre-fertilization foliar nutrient concentrations, it is now possible to determine whether Swan's foliar indices can be used to prescribe fertilizers (Table 6). On the positive side, a response to N or to N and P was predicted in black spruce and demonstrated in two of three experiments. Moreover, no response to K was predicted for either species and no response was noted. The response to N by jack pine, however, was not predicted, and despite the identification by foliar diagnosis of an acute deficiency in one pine experiment, no response to P was noted.

Table 6. The use of foliar nutrient concentrations to diagnose nutrient deficiencies in forest.[a]

Species	Age	Foliar[b] N	P	K	Response[c]
black spruce	65	mod-def	acute-def	suff-def	NP
black spruce	60	mod-def	suff-def	suff	N
black spruce	100	mod-def	mod-def	suff	ns
jack pine	55	suff	suff-def	suff	N
jack pine	45	suff-def	acute-def	suff	N

[a]Data from Foster (unpublished); Morrison et al. 1977a, b; Morrison and Foster 1979; van Nostrand and Bhure 1973.
[b]Swan (1970)
[c]Significant at .05 or better.

For several reasons, difficulties may be encountered with the interpretation of foliar concentrations. For example, foliar concentrations may not correspond with the physiological requirements of the tree because of luxury consumption of a nutrient. Also, trees can respond to nutrient stress by an internal translocation of elements from older to current tissue, since they retain their needles for 3 to 7 years. Rapid decline in concentration in older needles may be followed by premature needle abscission (Turner and Olson 1976, Miller et al. 1979) and a concurrent reduction in tree growth. Translocation may be particularly important to *Pinus* spp. which are well adapted to soils low in organic matter and exchangeable nutrients.

Soil Nutrients

Assessing the soil nutrient regime is difficult because the nutritional requirements of the various tree species are not yet fully known. With our current knowledge, indirect measures of soil fertility (e.g., soil parent materials, soil texture, nature of humus layer, presence or absence of seepage waters) may be as useful in assessing soil fertility as direct chemical tests currently in use.

In the first place, with a few exceptions (e.g., Ballard and Pritchett 1975), Leaf's (1967) statement on soil testing, although it pertains to the United States and to different tree species, is applicable to Canadian conditions. According to Leaf, "[f]orest soil researchers have not developed, for many of our tree species, adequate extractants and procedures to measure the 'available to trees' fraction of soil nutrient." In view of the importance of N to our forests, Tamm's (1977) observation that "[w]e have no commonly accepted method for assessing the active fraction of soil nitrogen supply..." is also particularly relevant.

Second, the heterogeneity of forest soils and the considerable extent of a tree's rooting system, both horizontally and vertically, pose particular problems with respect to selecting samples of soil for chemical analysis or for bioassay study that are representative of a forest's rooting zone.

Third, because forests have a long life, the potentially available nutrient-supplying power of the soil is as important as the readily soluble nutrient supply. In coniferous forests, particularly the boreal forest, the thick raw humus layers are especially important to tree nutrition. Although considerable information has been obtained on humus chemistry and biology (Bernier 1960, Bernier and Roberge 1962, Weetman 1962), particularly the reactions of fertilizers in humus (Knowles 1969, Salonius 1972, Roberge 1976), the role of humus in tree nutrition is still not fully understood.

Fourth, a tight cycle of nutrients is maintained between the trees and the surface soil so that release from humus provides a considerable part of the forest's nutrient requirement, particularly for mobile elements like K and Mg (Miller et al. 1979). Nitrogen and P are organically bound and are released very gradually from slowly decomposing humus. Accumulation of humus during the midlife of the forest is considered the cause of the general insufficiency of N in the northern coniferous forest (Weetman 1962).

Fifth, P uptake into trees is facilitated by mycorrhizal associations with trees. This symbiosis is a further complication in interpreting values of available P derived by soil chemical tests.

Sixth, mosses have a particularly important role in the nutrition of coniferous forests. Nutrients intercepted from rainfall and dustfall are released more rapidly from decomposing mosses than from the decaying tree litter (Bernier and Roberge 1962). Adventitious rooting within the humus and moss layers allows black spruce trees access to these nutrients.

Because many of these factors and others must be considered in the evaluation of soil fertility, one would expect great difficulty in selecting and measuring parameters of fertility that can be correlated with forest productivity. Heger (1971) found that 11 classes of drainage and parent materials were of no value in explaining differences in white spruce site index in Alberta.

Soil properties, however, including factors directly or indirectly reflecting soil nutrient regimes, have been closely correlated with the productivity of a site, and usually with site index (e.g., Pawluk and Arneman 1961, Wilde et al. 1964, Lowry 1975). The importance of keeping age and stocking of a forest constant when soil-site relationships are sought was emphasized by Duffy (1965) in reports on the influence of site on lodgepole pine (*Pinus contorta* L.) in Alberta. The studies of Wilde et al. (1964) and Pawluk and Arneman (1961), which demonstrated that jack pine production was related to soil fertility, were conducted in fully stocked natural stands of similar age or in even-aged plantations with controlled stocking.

The considerable range in dry-matter production and nutrient content within a species is demonstrated in Table 7 in a comparison of three 40- to

Table 7. Dry-matter and nutrient content (kg ha^{-1}) of 40- to 45-year-old jack pine forest.

Site class	Trees ha^{-1}	Dry matter	N	P	K	Ca	Mg
I[a]	1580	147 300	259	25	97	199	38
II[b]	2100	106 040	164	20	129	131	22
III[c]	3440	91 100	196	32	98	77	28

[a]Alban et al. 1978.

[b]Morrison and Foster 1977.

[c]MacLean and Wein 1976, 1977.

45-year-old jack pine forests from different soils. Differences in site quality and stand density are undoubtedly responsible for the yield and nutrient accumulation patterns exhibited by these forests. As these three forests are geographically widely separated, climatic variables may also contribute to the yield differences. As an example of the complex relationship between tree growth and site, Chrosciewicz (1963) found that regional macroclimate, soil moisture regime, soil texture and soil petrography all were important to the growth of fully stocked jack pine forest in northern Ontario. With regard to soil fertility he found that the highest pine site indices were associated with siliceous soil materials containing 30-40% basic particles and that site indices diminished when the content of such particles decreased to less than 10%.

Lowry (1975) studied site factors in relation to site index in 125 natural black spruce stands in eastern Canada. He found that N limited tree growth over a broad range of site conditions, P was often deficient on wetter sites, and Ca and Mg were deficient on organic soils.

The amount of an element that is absorbed by a plant is influenced by factors other than soil fertility, including interactions between elements both inside and outside the plant, and in particular is dependent on soil moisture. A lack of correlation between soil foliar nutrients and site in a study by Webber (1974) with Douglas-fir was related to variables other than soil nutrient parameters affecting tree metabolism.

Where moisture and temperature are limiting forest productivity, improving soil fertility by fertilization is not likely to increase tree growth. Webber (1974) emphasizes that, if future investigations on soil nutrient status are to be useful in forest fertilization evaluations, they must be conducted within a well defined framework of moisture regimes. In other words, there is an urgent need to stratify our sites by means of a site classifi-

cation system with a strong emphasis on nutrition and moisture so that we can identify those sites that will respond to fertilization.

WHERE ARE WE IN SOIL FERTILITY?

The results of a large number of fertilizer trials across Canada support the generalization that N is the most important element limiting the growth of coniferous forests. Growth responses to P and K have been reported, but only in combination with N.

On many of the less fertile, dry, coarse-textured soils, jack pine and Douglas-fir forest respond well to N or N in combination with P and K. A suspected relationship between response and site index for these species, indicating that the best volume growth occurs on the poorer sites, should be more vigorously tested over a wider range of site indices.

On coarse-textured soils abandoned from agriculture, fertilizers may be required not only to enhance growth but also to prevent the development of serious nutrient deficiencies in trees. On sandy loams and clay loams abandoned from agriculture, the level of response of juvenile hardwoods to fertilization indicates that these soils contain sufficient nutrients to support the early growth of newly established forest.

The average growth response to fertilizers by western hemlock, white spruce, red spruce, black spruce and balsam fir has been less than the response by pine and Douglas-fir. Information relating response-to-fertilization to nature of soil materials for these species is needed so that species-site combinations can be identified where fertility problems exist.

Soil chemical analyses useful for predicting response to fertilization have not been developed. Considerable progress has been made toward the use of foliar diagnosis for detecting nutrient deficiencies in trees. The methodology for foliar sampling has been developed and for some species critical foliar levels have been published. Although present foliar diagnosis may be useful for detecting severe deficiencies, the technique needs to be more fully developed before it can be used for prediction purposes.

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